Neutron Imaging of Advanced Transportation Technologies

Todd J. Toops (PI)

Email: toopstj@ornl.gov
Phone: 865-946-1207

Martin L. Wissink, Charles E.A. Finney, Eric J. Nafziger, Derek A. Splitter, Jonathon Willocks

Oak Ridge National Laboratory
National Transportation Research Center

2018 U.S. DOE Vehicle Technologies Office
Annual Merit Review

June 19, 2018 Project ID: ACS052

Project Overview

Timeline

- Year 2 of 3-year program (FY17-19)
  - 2016 Lab Call Task 7 in ORNL project "Multi-cylinder Advanced Combustion Engine Development and Controls"
  - New lab call for FY19, proposing continuing work

Budget

- FY2018: $300k
- FY2017: $185k
  - Additional $300k invested for detector development

Partners

- BES-funded neutron scientists and facility operation
- Academia
  - University of Tennessee
  - Boston University
- Industry
  - Bosch, GM, Continental Automotive

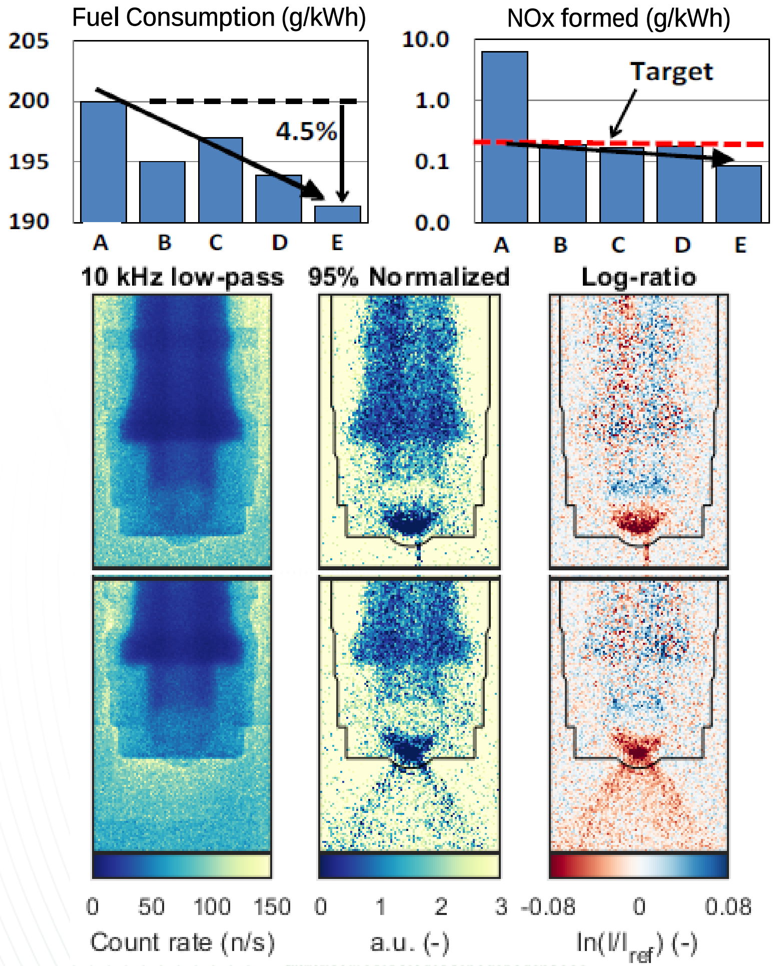
Barriers

- **2.3.1B: Lack of cost-effective emission control**
  - Improved regeneration efficiency in particulate filters (PFs)
- **2.3.1C: Lack of modeling capability for combustion and emission control**
  - Improved models of fluid flow inside fuel injectors
  - Need to improve models for effective PF regeneration with minimal fuel penalty
- **2.3.1.D: Durability**
  - Fuel injector durability
  - Potential for PF thermal runaway
  - Ash deposition and location in PFs which limit durability

Objectives and Relevance

Implement non-destructive, non-invasive neutron imaging technique to improve understanding of advanced vehicle technologies

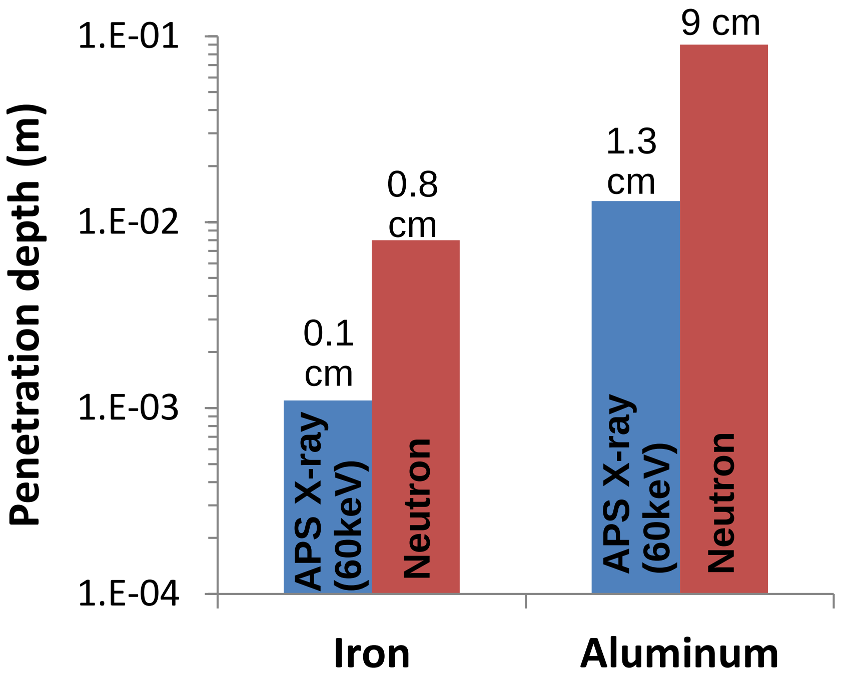
- Injectors: gasoline direct injection (GDI)
  - Goal: Visualize internal flow dynamics
    - Ball and needle wobble/oscillation
    - Fluid density variation
  - Aid model development; injector design
    - **Injector design significantly influences efficiency and emissions***
  - Diesel and urea also possible
- Particulate filters (PF)
  - Recent effort primarily moved to other projects, but technique developed here
  - Both gasoline and diesel PFs
  - Comprehensive, quantitative device analysis targeting model parameters

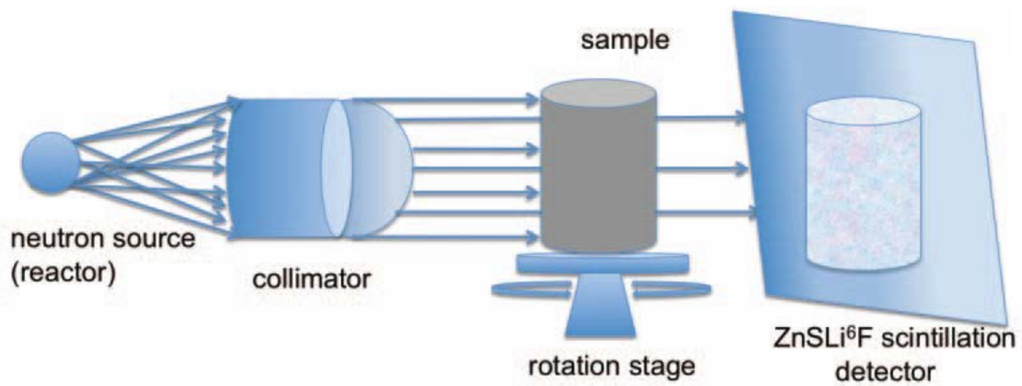


* - e.g., Keith Confer (Delphi), "Gasoline Ultra Fuel Efficient Vehicle", 2012 DOE AMR, Crystal City, VA, ACE064, May 18, 2012.

Neutrons can penetrate metals while still strongly interacting with light elements

- Neutrons are heavily attenuated by some light elements (^{1}H, ^{10}B, etc)
  - Can penetrate metals with minimal interactions
  - Highly sensitive to water and hydrocarbons/fuel
  - Image is based on absence of neutrons
- X-ray absorption increases for heavy/dense elements



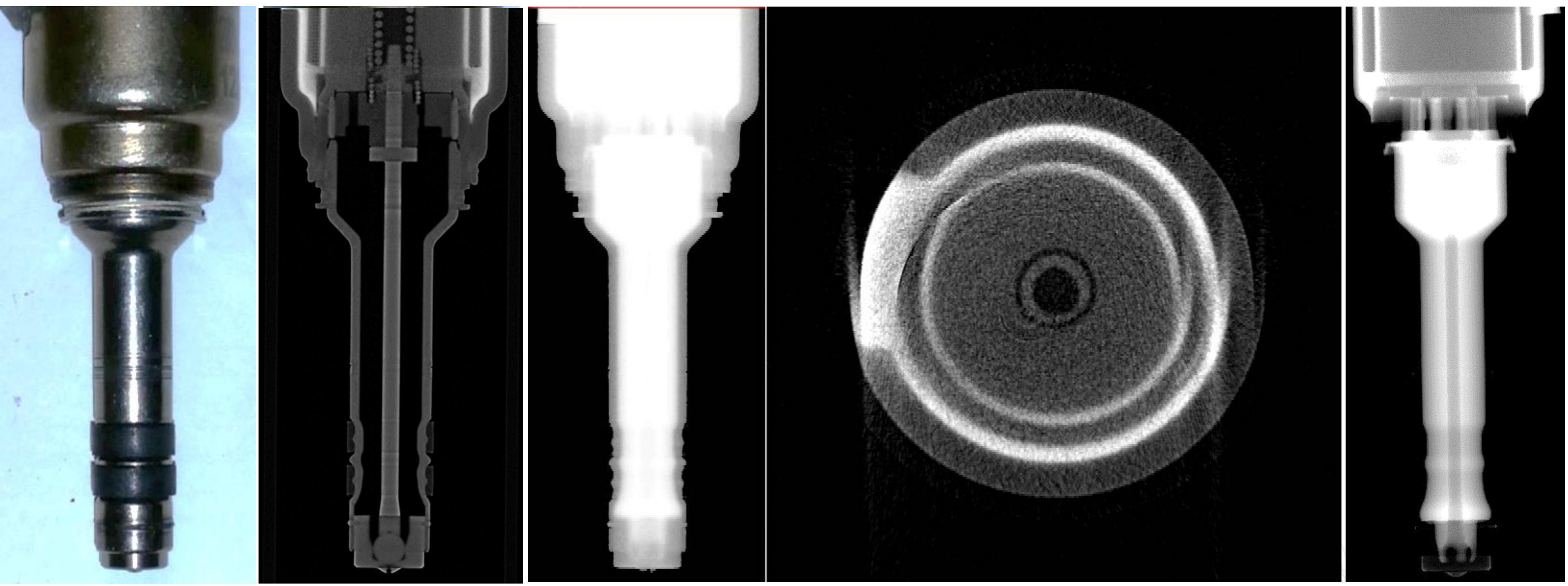


Neutron imaging is a complementary analytical tool

Attenuation Coefficient Reference: N. Kardjilov's presentation at IAN2006
http://neutrons.ornl.gov/workshops/ian2006/MO1/IAN2006oct_Kardjilov_02.pdf
Neutron Penetration depth : R. Pynn, "Neutron scattering: a primer." *Los Alamos Science* 19 (1990): 1-31. APS X-ray penetration depth: C. Powell, personal communication.

Complete sample analysis can be achieved with non-destructive techniques

- Samples can be analyzed at one cross-section or a complete reconstruction can provide a cross-section of the entire sample
  - Originally ~50 microns achievable at ORNL's High Flux Isotope reactor (HFIR)
  - As low as 10-20 microns possible with MCP (Micro-Channel Plate) detector
- Illustration of technique on GDI-based injector with fuel inside:



Empty Fuel-filled H-containing

Milestones

- Complete a high resolution computerized tomography scan of the ECN spray G injector body and share results with the ECN community (9/30/2017).
  - **Completed**
- Capture Neutron imaging sequence of double injection event under ECN-relevant conditions (6/30/2018).
  - **Completed**
- {SMART} Provide relevant fluid dynamics data from neutron imaging to the ECN research community for three conditions using iso-octane (9/30/2019).
  - **On track**

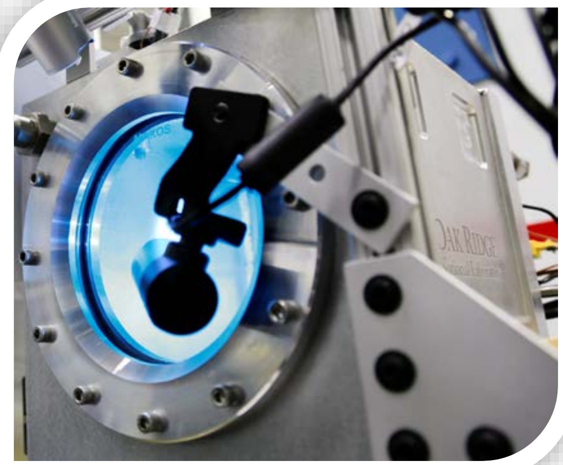
Collaborations

- **Basic Energy Sciences** (Hassina and Jean-Christophe Bilheux, Lou Santodonato)
  - High Flux Isotope Reactor (HFIR); Spallation Neutron Source (SNS)
  - Detector development and operation of beamline facilities
  - Scientists' time, data reconstruction, analysis and writing publications
- **University of Tennessee** (Jens Gregor, Alex Pawlowski)
  - JG: Developing algorithms for improving contrast, 3-D tomography and removing artifacts
  - AP: Bredesen Center Fellow, CAD development, image analysis
- **GM** (Ron Grover, Scott Parrish)
  - Coordination of ECN-style injectors
- **Bosch** (Philippe Leick)
  - Donation of single-hole large-bore injector
- **University of California** (Anton Tremsin)
  - Development and installation of MCP detector at ORNL
- **Boston University** (Emily Ryan, Sheryl Grace, Glynn Holt, Huy Do)
  - Development and multiscale validation of Euler-Lagrange based computational methods for modeling fluid dynamics in fuel injectors
- **MIT Consortium** (J. Kamp, A. Sappok, V. Wong, 12+ members)
  - Ash-filled DPFs, X-ray CT-scans, detailed analytical discussions

Approach

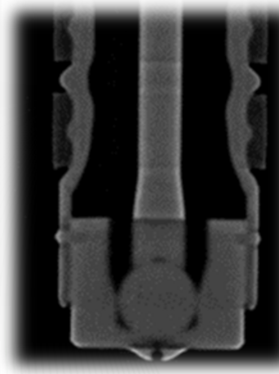
Receive or obtain relevant devices

Record raw images of devices with neutron beam, scintillator and/or MCP detector

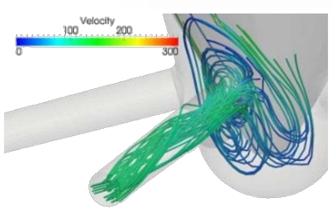


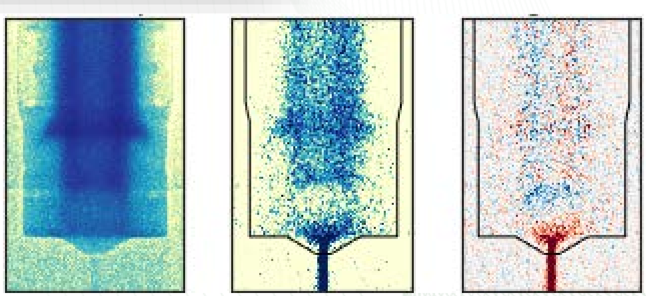
Non-destructive technique allows multiple studies to be performed on single commercial or prototype device

Reconstruct device or enhance contrast using imaging software



Technique being employed to study both internal geometries and fluid flow during operation; linked to HPC efforts





K. Neroorkar, R.O. Grover, Jr. et al., “Simulations and Analysis of Fuel Flow in an Injector Including Transient Needle Effects”, ILASS-Americas 2012, San Antonio, TX.

Summary of Technical Accomplishments

- Dynamic imaging of fluid dynamics inside GDI-based injectors
  - Analyzed flow in three injectors with single and multiple injections using iso-octane at two chamber conditions
  - All injectors exhibited oscillation of ball and pintle during injection
  - Developing technique to quantify amplitude and frequency of oscillations – will compare to acoustic data
- Neutron CT scan of single-hole large-bore Bosch injector
  - Will combine neutron CT data with ANL* high-definition tip X-ray CT scan (as done previously for Spray G injector)
- GDI-generated particulate study in GPFs
  - Particulate characteristics continue to demonstrate very different behavior compared to diesel-based particulate

* ACS010 Powell

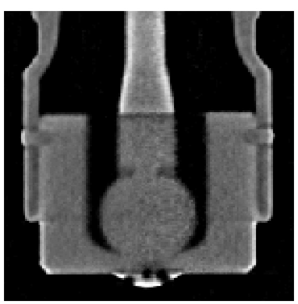
Technical Accomplishments

- Dynamic imaging of fluid dynamics inside GDI-based injectors
- CT scan of single-hole large-bore Bosch injector
- GDI-generated particulate study in GPFs

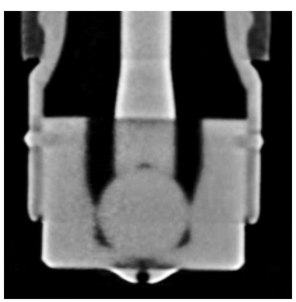
Injectors

Injector	Hole diameter (microns)	Nozzle shape
8-hole small bore (Spray G copy)	170	Step hole
1-hole small bore (Spray G copy)	170	Step hole
1-hole large central bore	700	No step/ counterbore

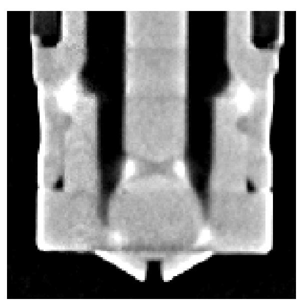
8-hole small bore



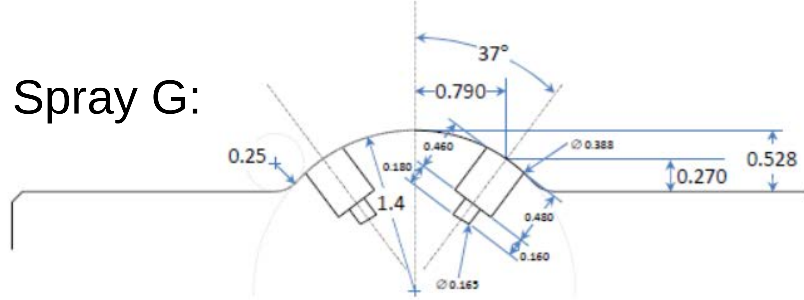
1-hole small bore



1-hole large bore



Spray G:

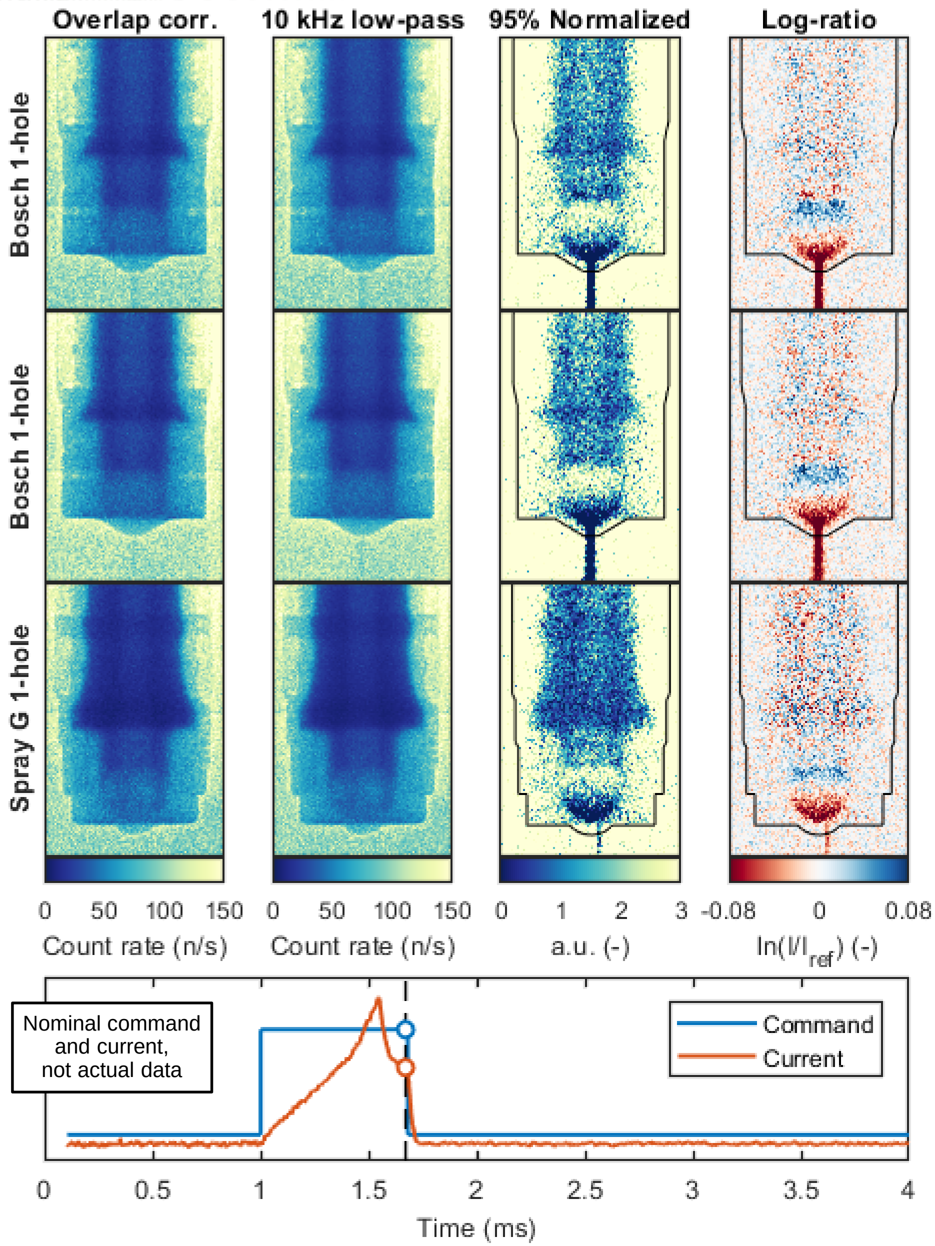


http://public.ca.sandia.gov/ecn/G/compMeth/Mesh&Modeling.php

Bosch large-bore:

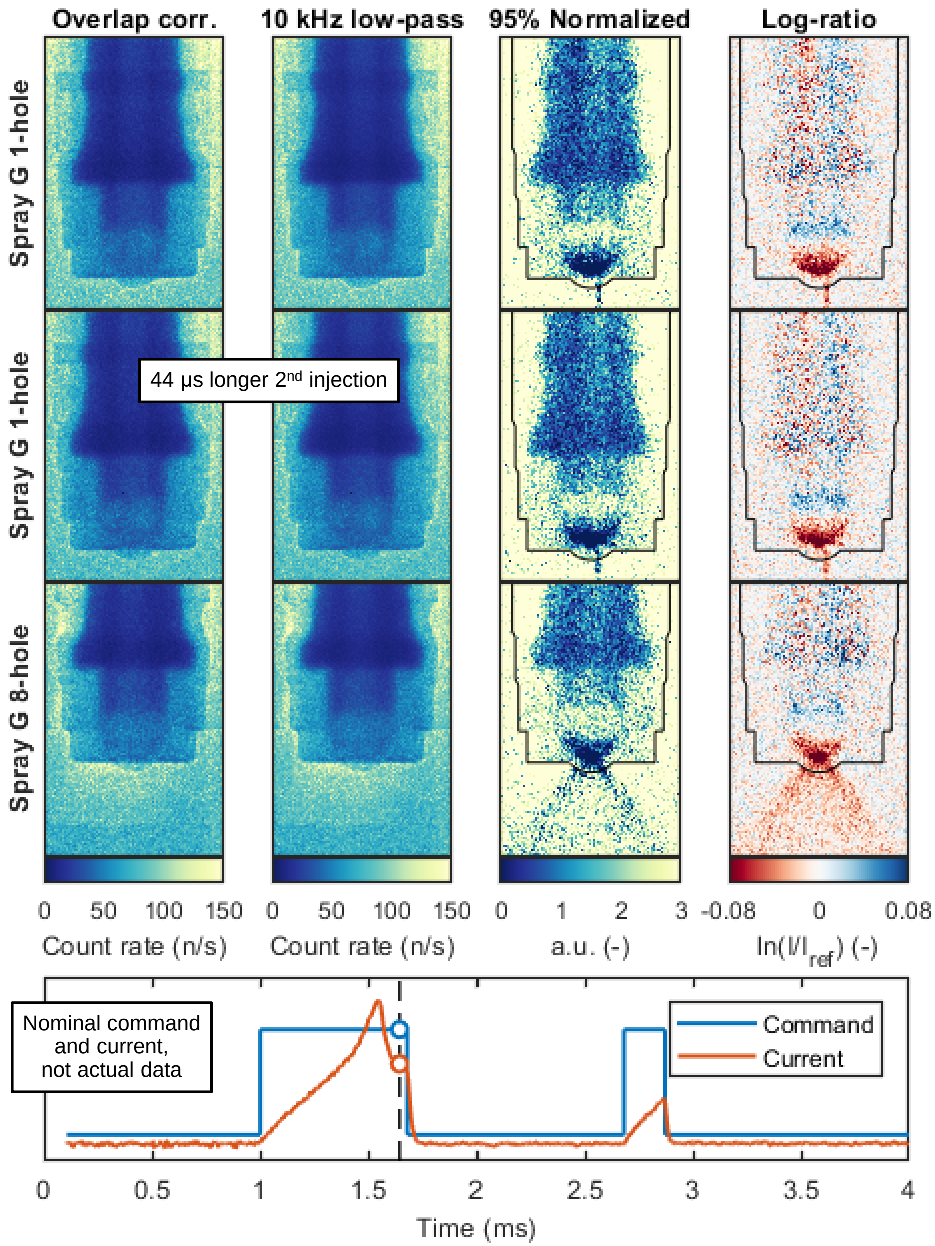
- Discussions with Bosch resulted in donation of a single-hole large bore GDI-style injector
- Large bore size increases relative resolution of flow dynamics

Single injection results



- 5 μs frames, ~25 micron pixels
- Partially normalized images visually highlight movement
- Log-ratio normalized images quantify difference from reference (blue = less fuel, red = more fuel)
- Needle movement in log-ratio images toward blue, away from red
- Ball lift and wobble visible during injection
- Needle displacement/oscillation visible during and after injection
- Analysis to quantify movement currently underway

Multiple injection results



- 5 μs frames, ~25 micron pixels
- Needle movement in log-ratio images toward blue, away from red
- Ball lift and wobble visible during injection
- Needle displacement/oscillation visible during and after injections
- Small changes to second injection duration have significant impact on needle motion (ballistic event, non-linear)
- Analysis to quantify movement currently underway

Attenuation modeling

Lambert-Beer Law:

$$T = \frac{I(\lambda)}{I_0(\lambda)} = e^{-\mu(\lambda)\Delta y}$$

μ is the attenuation coefficient
Δy is the sample thickness

$$T(t) = T_A \times T_B \times T_C \times \cdots = e^{-(\mu_A d_A + \mu_B d_B + \mu_C d_C + \cdots)}$$

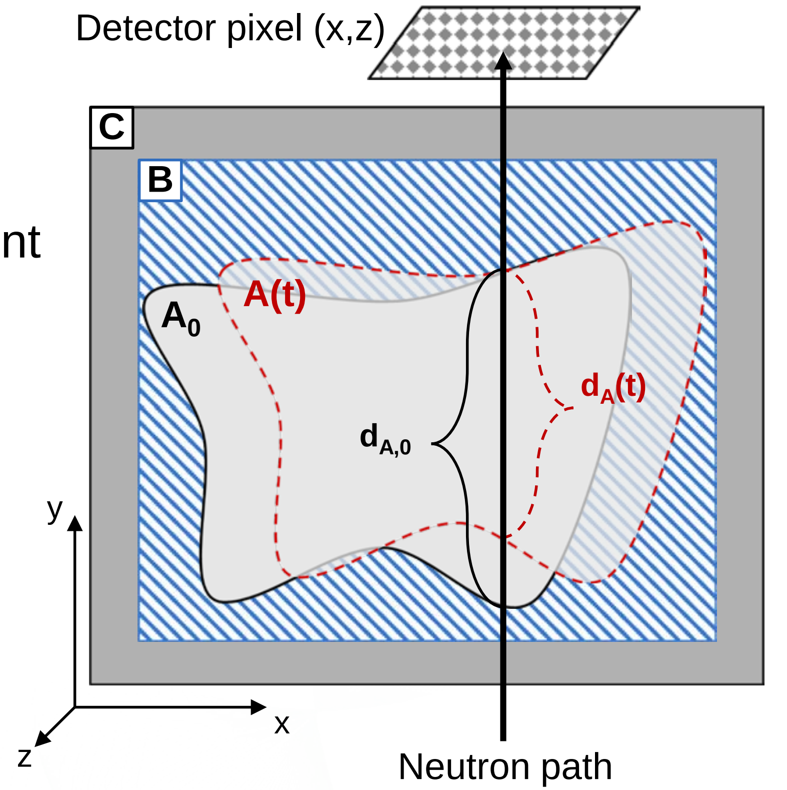
If all interfaces are static except for A/B:

$$\frac{T(t)}{T_0} = \frac{T_A \times T_B \cancel{\times T_C \times \cdots}}{T_{A,0} \times T_{B,0} \cancel{\times T_{C,0} \times \cdots}}$$

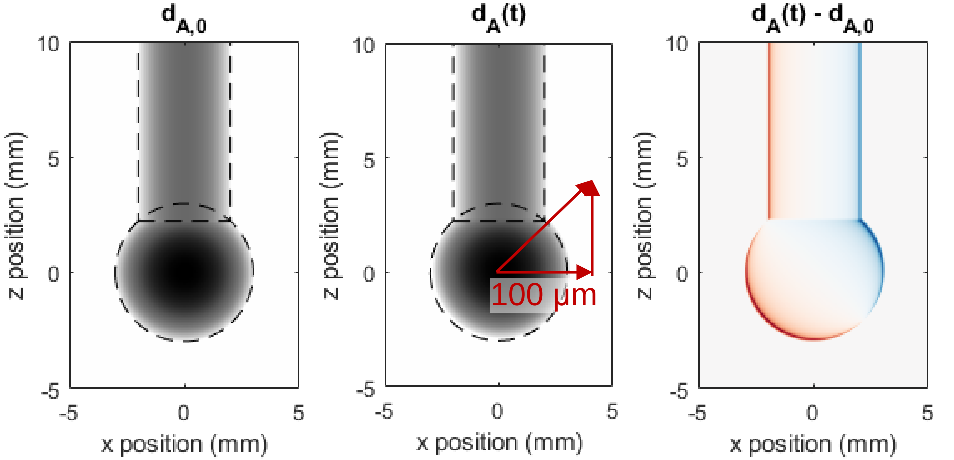
$$= e^{-[\mu_A(d_A(t) - d_{A,0}) + \mu_B(d_B(t) - d_{B,0})]}$$

$$d_{A,0} + d_{B,0} = d_A(t) + d_B(t)$$

$$\boxed{\ln\left(\frac{T}{T_0}\right) = (\mu_B - \mu_A)(d_A(t) - d_{A,0})}$$

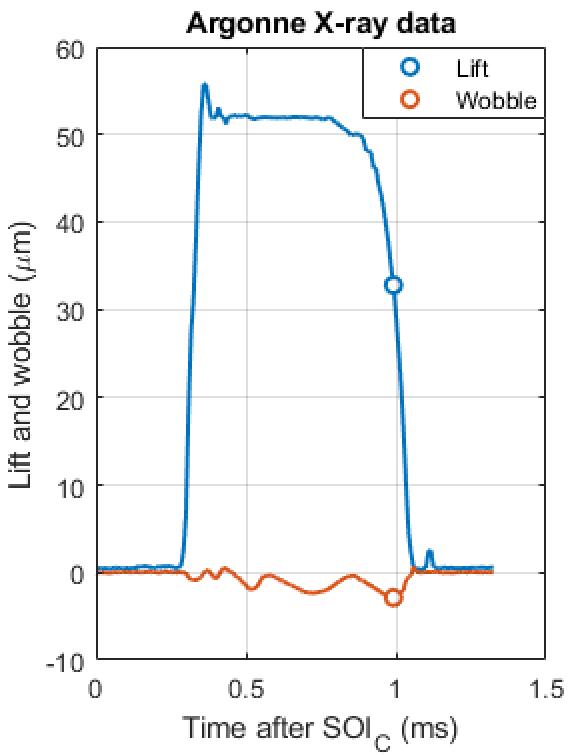


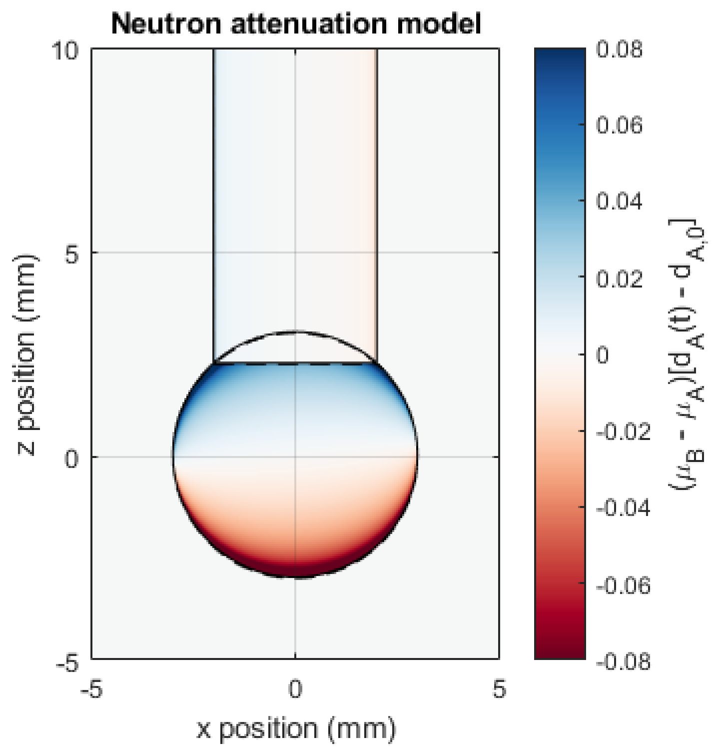
Example with Spray G needle geometry:

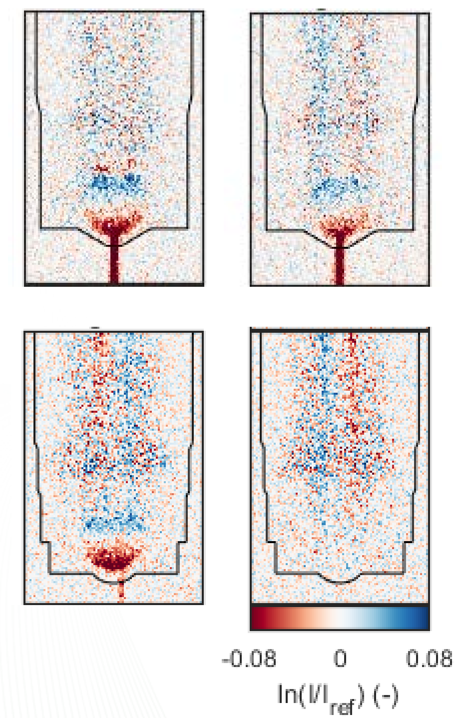


Comparison to X-ray lift and wobble data

- Argonne X-ray measurements of Spray G #28 ball lift and wobble available on ECN website: https://ecn.sandia.gov/G/data/needleLift/SprayG28_Xray_Needle_Lift.xlsx
- If we assume motion purely rigid translational, there is very little shifting of the pintle relative to lift







- It is evident from normalized neutron images that relatively large deflections occur in the needle during and after injections, whereas ball wobble is restricted by guides
- Work is ongoing to quantify displacement and identify suitable model of motion – collaborators at Boston University have identified acoustic signatures that indicate cantilever beam vibration
- Much potential in this space for further investigation and targeted experiments

Technical Accomplishments

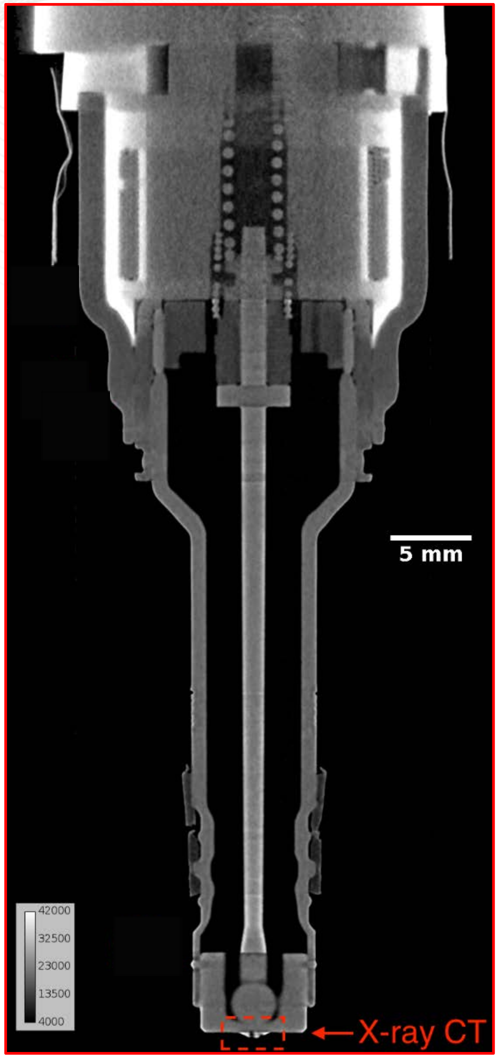
- Dynamic imaging of fluid dynamics inside GDI-based injectors

- CT scan of large-bore single-hole Bosch injector

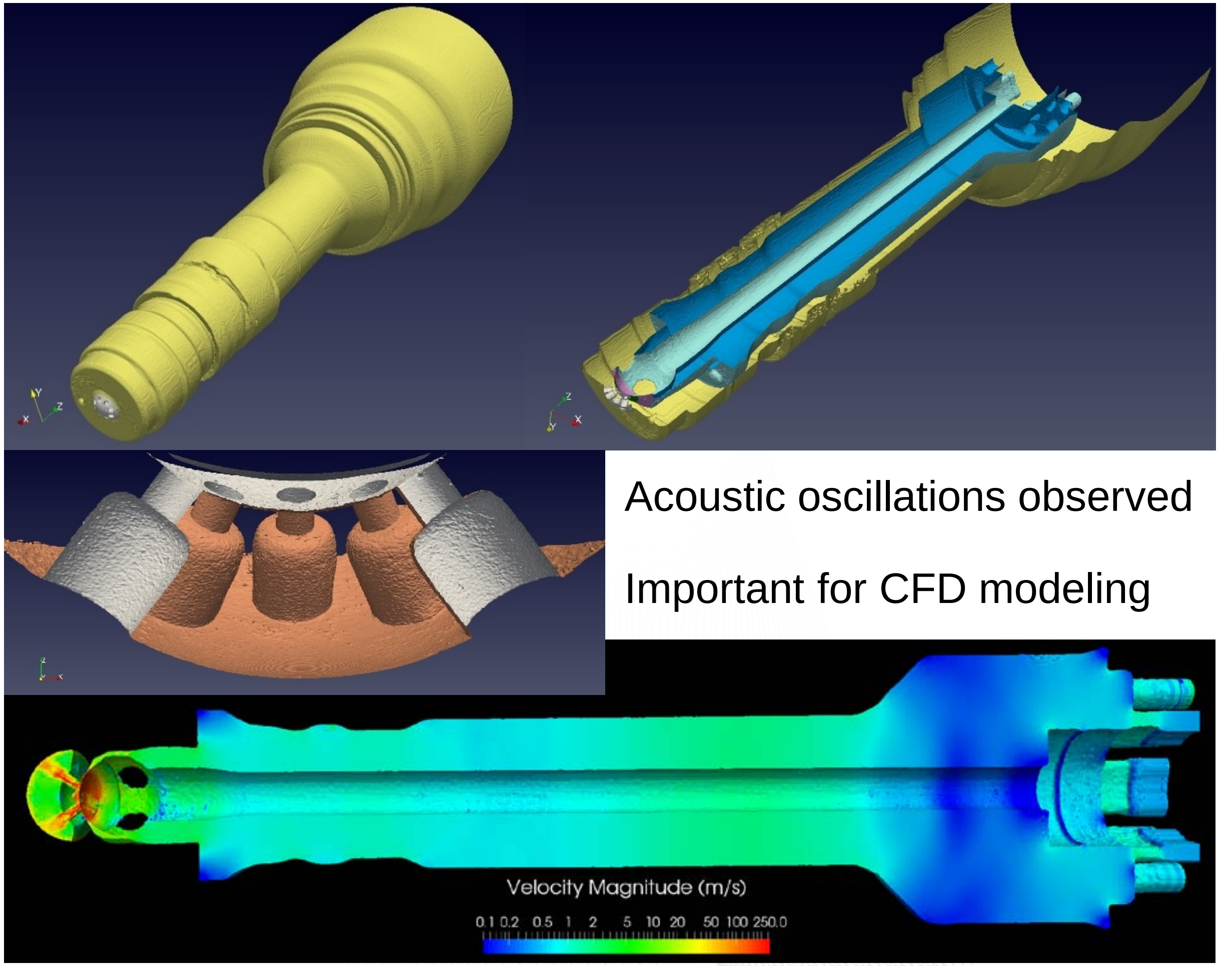
- GDI-generated particulate study in GPFs

Prior year AMR: Collaboration with ANL produced full scan of Spray G injector with maximum resolution

Neutron CT



Gridding & CFD by D.J. Duke *et al.* (ANL)*

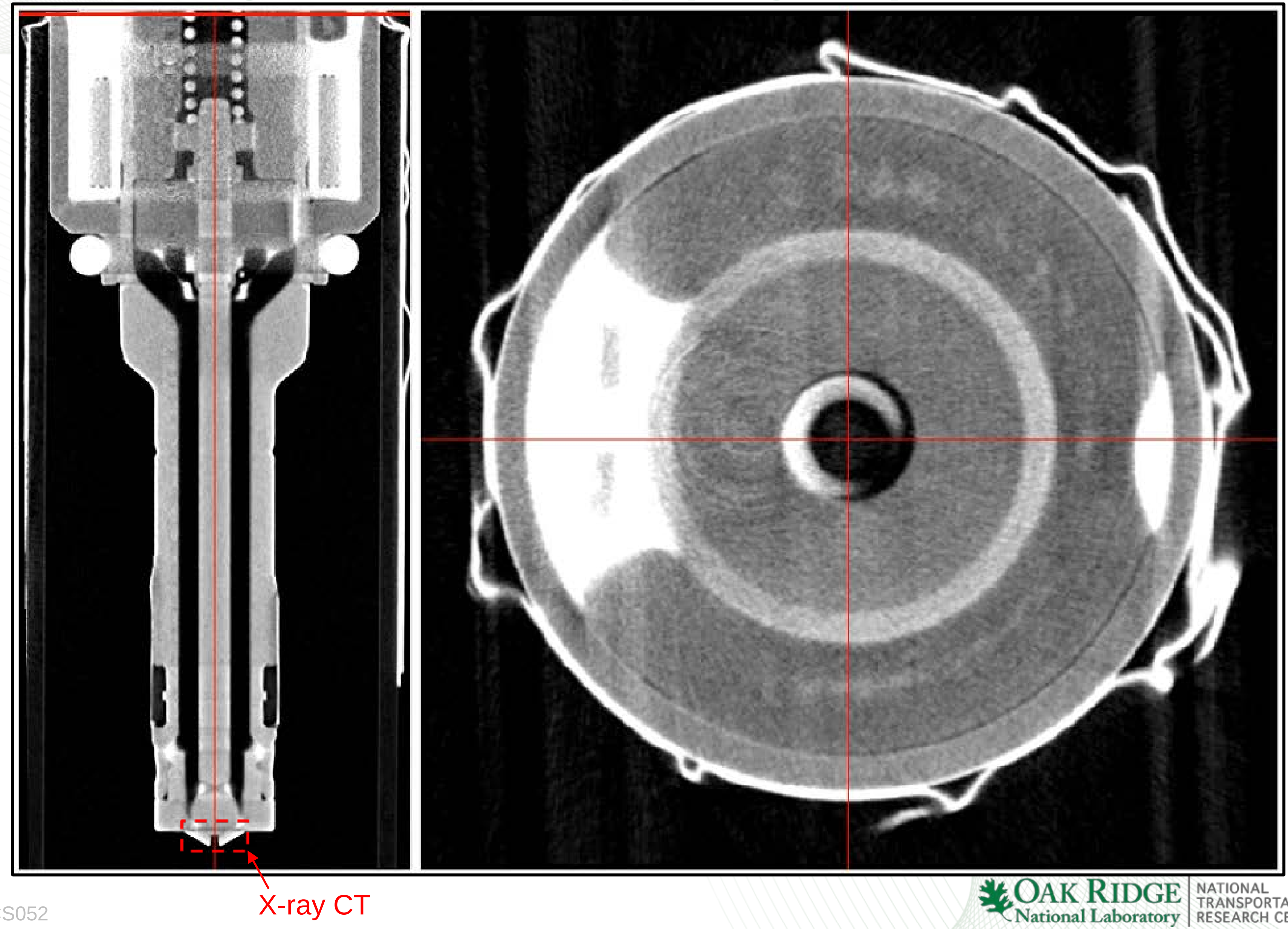


Acoustic oscillations observed

Important for CFD modeling

* ACS010 Powell

FY19: Collaboration with ANL to produce full high-res scan of Bosch large-bore injector (in progress)

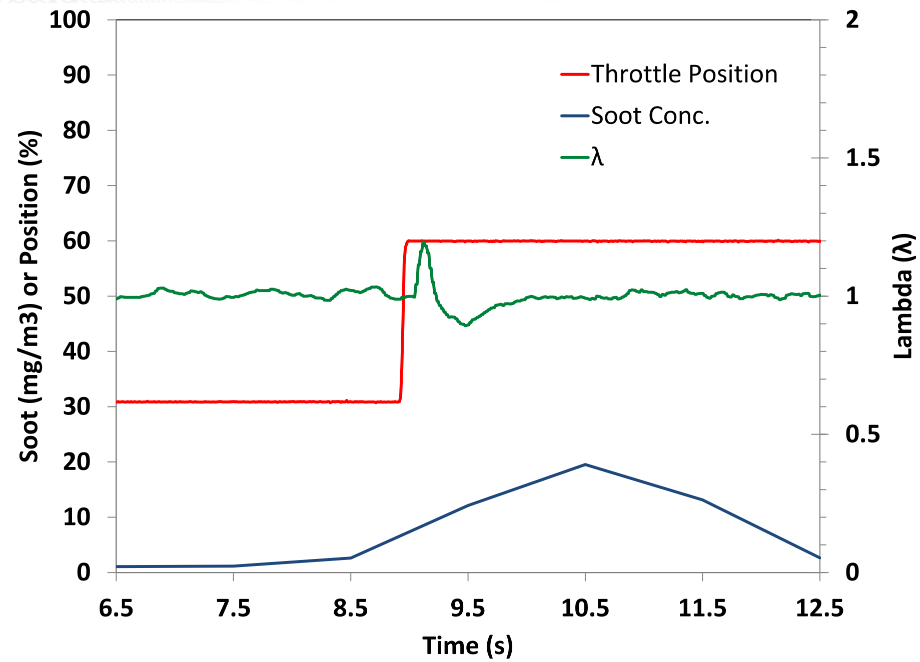


Oak Ridge National Laboratory | National Transportation Research Center

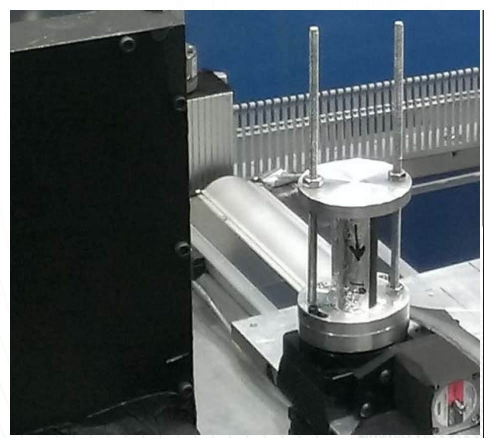
Technical Accomplishments

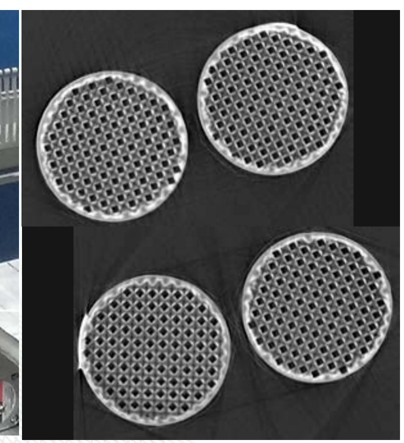
- Dynamic imaging of fluid dynamics inside GDI-based injectors
- CT scan of large-bore single-hole Bosch injector
- GDI-generated particulate study in GPFs

GPF particulate study using tip-in



- GDI stoichiometric engine operated to mimic "tip-in" point of acceleration
  - Novel approach designed to capture mode of maximum PM generation
  - Brief period of rich operation (λ = 0.91), medium-high load
  - Sample holder with four 1" GPFs
    - Allows repeated measurements
    - Filled to nominal 4 g/L
- Characterize with original CCD detector at HFIR

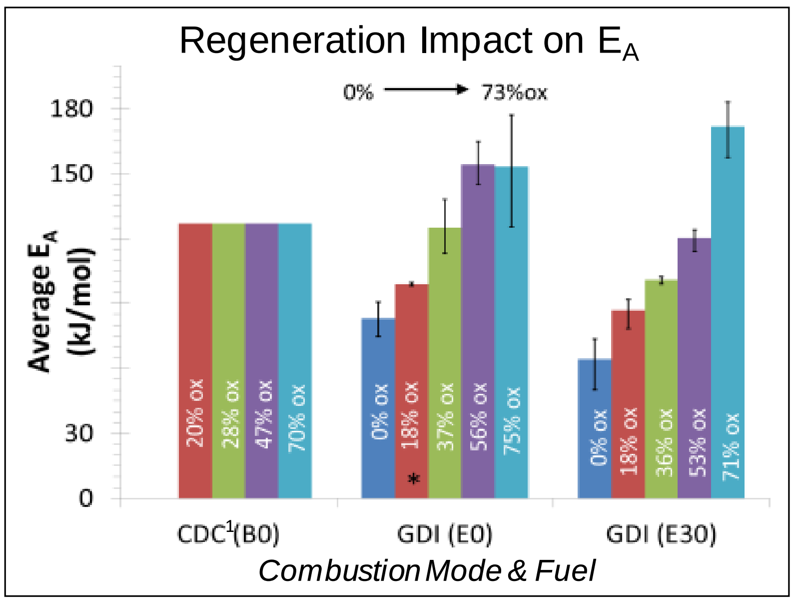


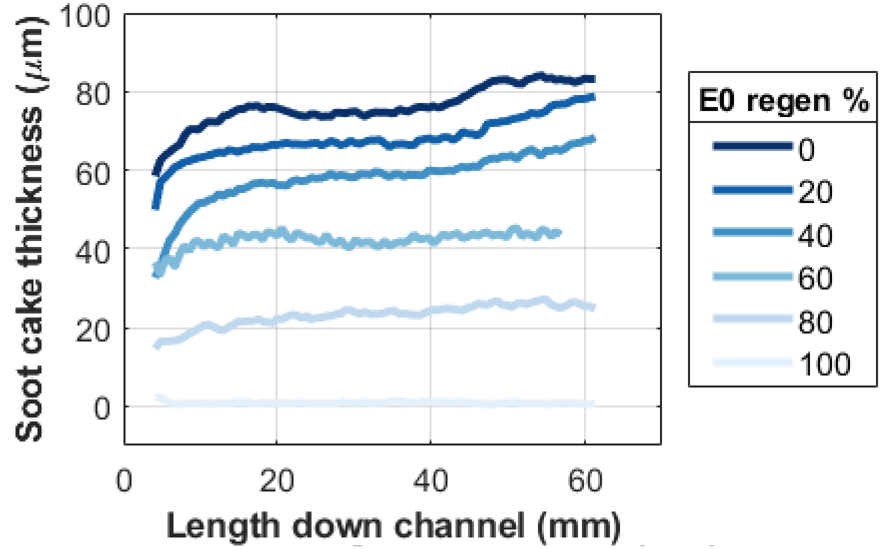


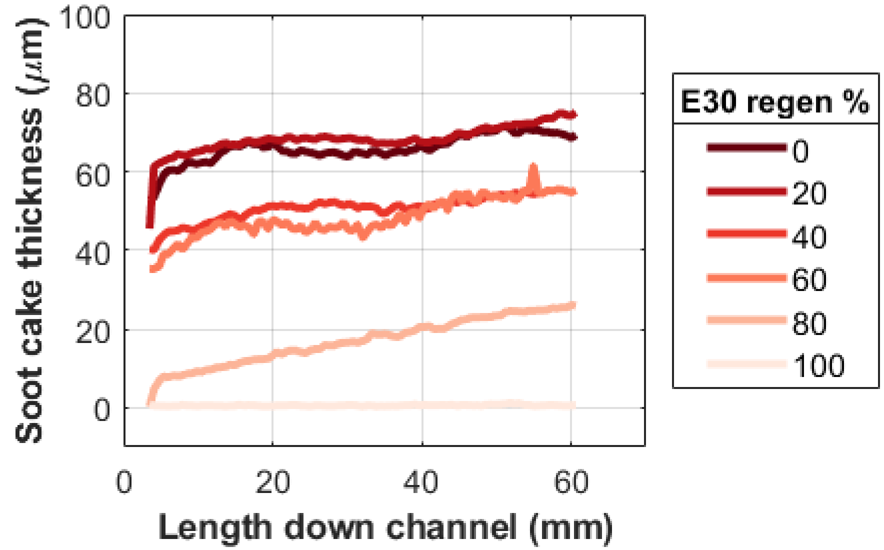
OAK RIDGE National Laboratory | NATIONAL TRANSPORTATION RESEARCH CENTER

Analysis of GPF particulate deposition and oxidation behavior illustrates its reactivity is different from diesel

- Coordinated with project in Co-Optima program on fuel effects on PM formation/reactivity; E0 vs. E30
- Soot cake is initially <80 microns and appears to slightly increase in thickness along flow channel
- Minimal decrease in soot cake layer during first 20% regen; after 40% regen, reduction observed
  - Likely adsorbed HC removal
  - Above 40% regen some differences being observed between E0 and E30
- Oxidation data shows varying Ea in w/ regen







[1]Pihl, J.; et.al. (2013) *Top. Catal. 56:499*

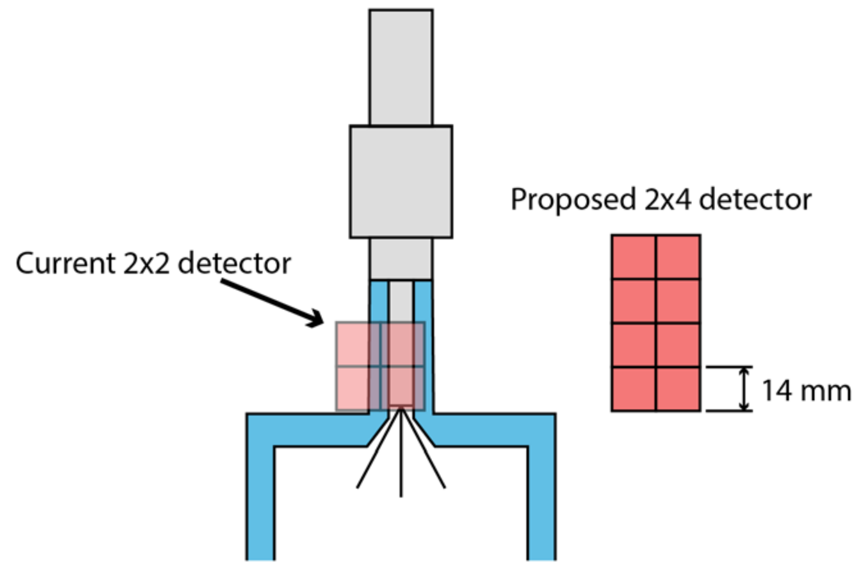
Remaining Challenges & Barriers, and Proposed Future Work

Remaining Challenges:	Future Work:
• Translation of dynamic fuel injection data to modeling	• Quantitative analysis of needle and ball motion during injection event • Collaborations ongoing with ANL, Boston U., and U. Tennessee • Complete design and fabrication of third-generation injector chamber to enable measurements of entire needle deflection • Injector timing and chamber optimization to increase data throughput • Detector optimization to improve contrast in low-intensity regions
• Unknown effects of double injection events	• Explore inter-injection sac effects, needle/ball motion during double injections • Flash boiling and non-flash boiling effects on double injections. How much liquid enters the sac, rate of dribble?

Any proposed future work is subject to change based on funding levels

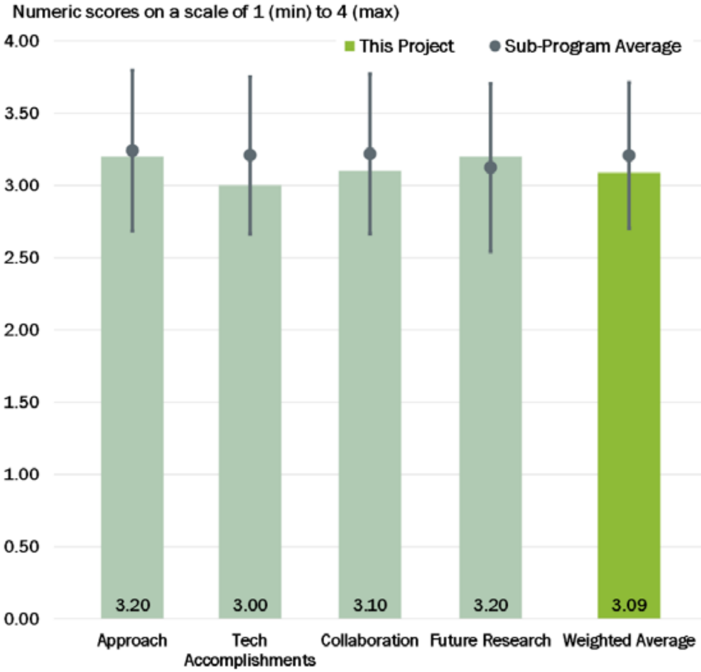
New chamber design to image internal region and reach Spray G conditions (300 °C, 6 bar)

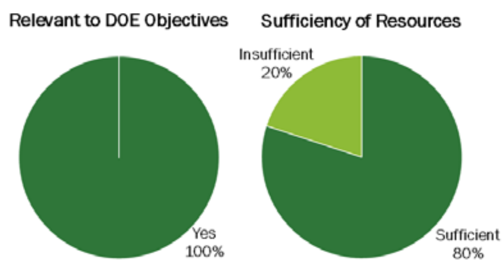
- Current chamber designed for imaging spray & bottom of nozzle
- Argon jets w/ high flowrate required to mitigate high-attenuation fuel & oil films that deposit on walls
- New concept focused on imaging from the tip up
- Keeps injector out of hot environment, removes film concerns
- More compact to get closer to detector for maximum resolution



Material	Transmission @ 1 cm (2 Å neutrons)	Half life	Notes
Al	0.899	Al-28: 2.3 m	Poor strength at high T
Fe (all steels)	0.286	Fe-55: 2.7 y Fe-59: 45 d	Makes gamma rays
Ti	0.532	Ti-50: 5.8 m	Expensive

Responses to 2017 Reviewers (5)





- **Resources (20% Insufficient)**
  - Comments: *Information gained from this project is complementary to ANL and SNL efforts and more resources needed to increase accomplishments*
  - Response: moving in that direction

- **Approach (3.2/4.0)**
  - Comments: *good example of using tools and capabilities that are only available at NLs to diagnose engine related problems … **not clear how project addresses stated barriers**… **injector durability***
  - Response: **improved understanding of filter regeneration to predict how much fuel is necessary to regenerate … techniques can be used to study internal fouling in injectors**
- **Technical Accomplishments (3.0/4.0)**
  - Comments: *good progress in acquiring detailed images of fluid dynamics in injectors and regen phenomena in PFs… **beam time appears to be an issue**… **improved resolution needed***
  - Response: **recently turned down beamtime to allow more analysis and chamber upgrades (1-2/yr adequate at current funding) … new detector being developed as well as new spray chamber for improved resolution and faster data acquisition**
- **Collaborations (3.1/4.0)**
  - Comments: *collaboration with ANL gives nice synergy… **not clear if modeling community can make use of imaging data** … **new collaborations should be sought with Bosch/Delphi***
  - Response: **focus of current efforts is to make analysis of data in a manner that is more accessible to modeling community (ECN, Boston-U, etc.) … new discussion/injectors provided by Bosch**
- **Future plans (3.2/4.0)**
  - Comments: ***discussion should be initiated with PF and injector suppliers** … good plan for carrying work forward*
  - Response: **PF discussions have been ongoing especially with OEMs and in-use issues; Bosch added**
- **Relevance (100%)**
  - Comments: *generates new knowledge about fundamental phenomenon that industry would like to know …improved understanding of particulate behavior can help engine designers improve engine efficiency*

Summary

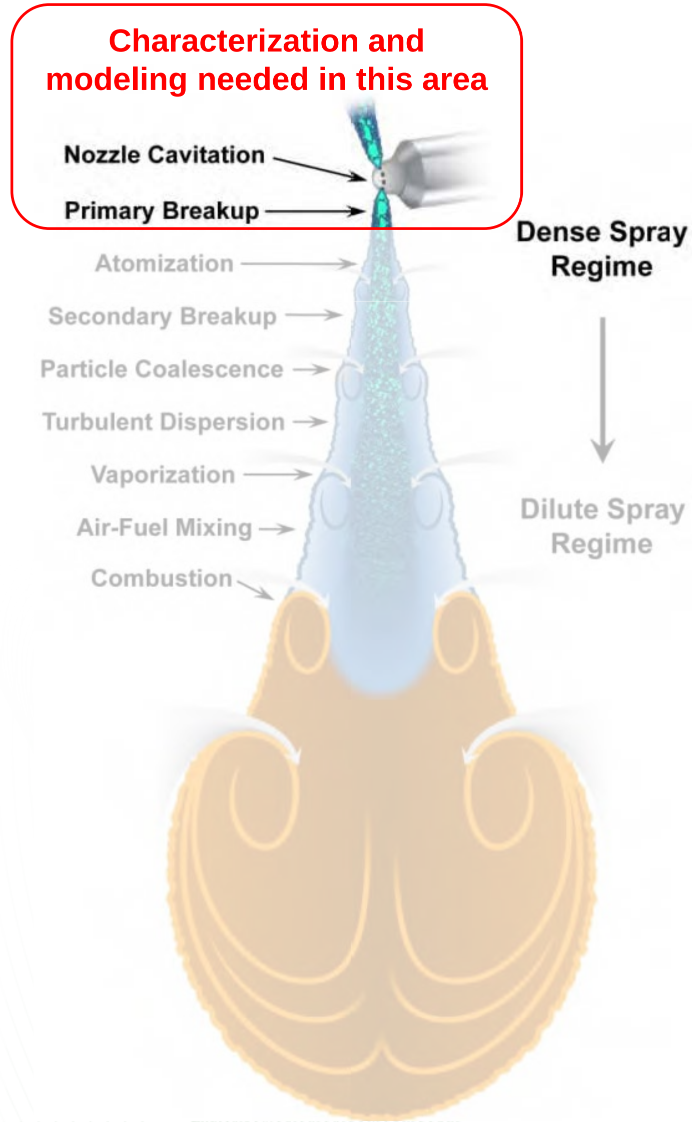
- **<u>Relevance</u>:**
  - Non-destructive, non-invasive analysis to improve understanding of lean-burn vehicle systems, targeting fuel economy improvements and durability; focused on fuel injectors and particulate filters
- **<u>Approach</u>:**
  - Neutron Imaging as a unique tool applied to automotive research areas to visualize, map and quantify deposits in engine parts as well as investigating internal injector dynamics
  - Fuel injectors being studied under both static and dynamic conditions; PFs under static conditions
- **<u>Collaborations</u>:**
  - Partners include BES-funded scientists and programs, Industrial (GM and Continental Automotive), and Academic (MIT, U. Tennessee, U. California and Boston U.), ECN
- **<u>Technical Accomplishments</u>:**
  - Dynamic imaging of flow in three injectors with single and multiple injections using iso-octane at two chamber conditions
    - All injectors exhibited oscillation of ball and pintle during injection, significant effects with multiple injections
    - Developing techniques to quantify amplitude and frequency of oscillations
  - Completed neutron CT scan of single-hole large-bore Bosch injector
  - GPF characteristics continue to demonstrate different behavior compared to diesel-based particulate
- **<u>Future Work</u>:**
  - Quantitative analysis of needle and ball motion during injection event
  - Collaborations ongoing with ANL, Boston U., and U. Tennessee
  - Design/fabricate of 3rd-generation injector chamber to enable measurements of entire needle deflection
  - Injector timing and chamber optimization to increase data throughput
  - Detector optimization to improve contrast in low-intensity regions

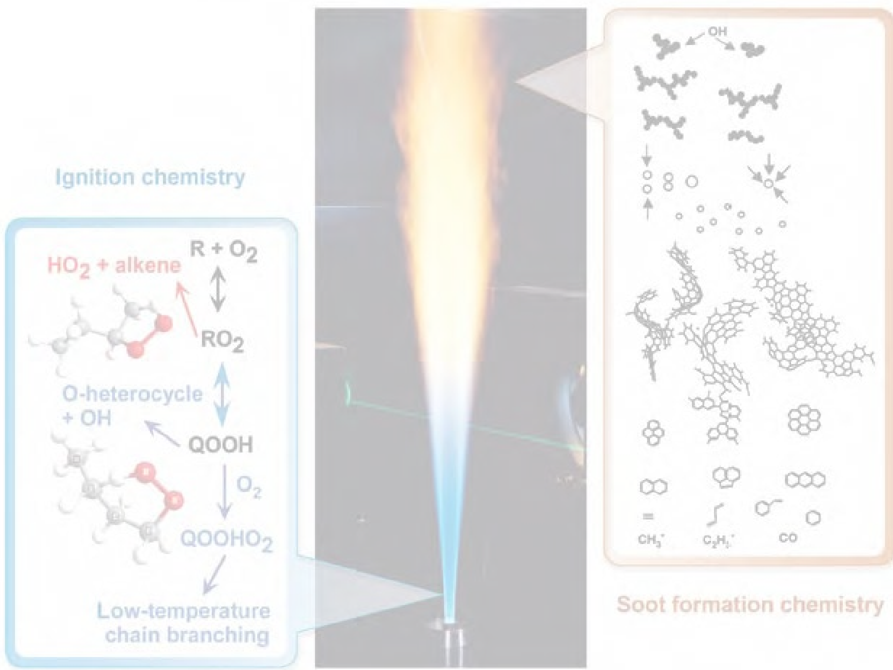
Any proposed future work is subject to change based on funding levels

Technical back-up slides

Spray pattern and impact on product formation has been heavily studied, but critical information is still needed

- Events occurring in the injector impact the spray dynamics and product distribution
  – Products form at different points in fuel spray
- Knowledge of how internal dynamics/events affect the spray pattern are not well understood
- Improved diagnostics critical to make this connection

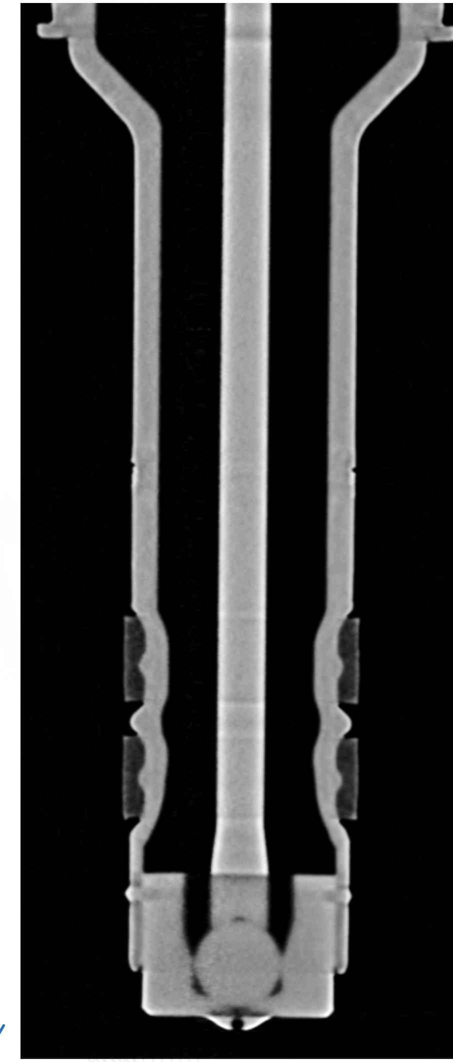


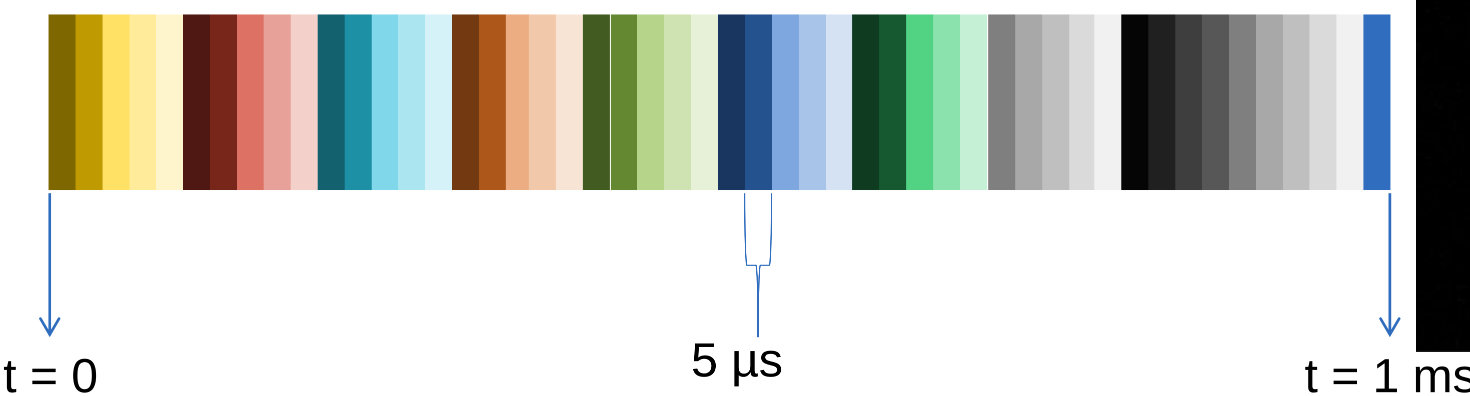


DOE report, "A Workshop to Identify Research Needs and Impacts in Predictive Simulation for Internal Combustion Engines (PreSICE)", March 3, 2011.

Employ stroboscopic technique to image internal fluid with 680 µs injection, 5 µs resolution

- Variables include: rail pressures, heated nozzles and evacuated chamber
  - Highest rail pressures (GDI: ~200 bar)
- Injection timing for composite image:
  - 680 µs injection with 5 µs resolution
  - Targeting 5-10 s of neutron exposure for each 5 µs frame
  - This is a stroboscopic ensemble (1-2 million injections), NOT a single shot study

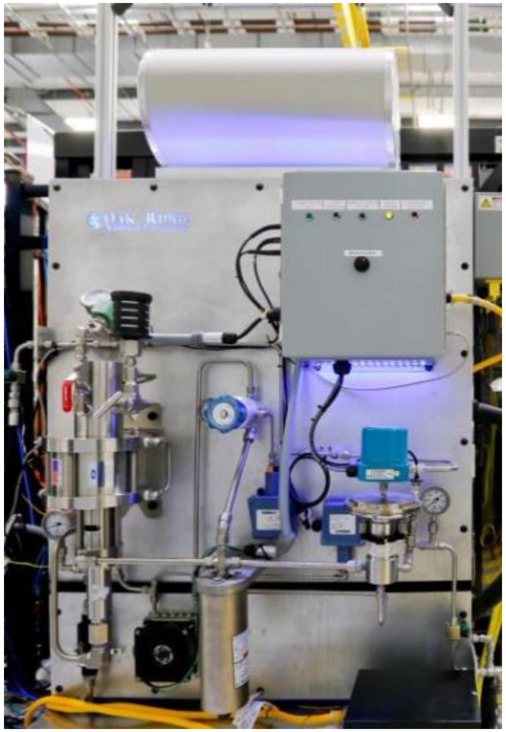


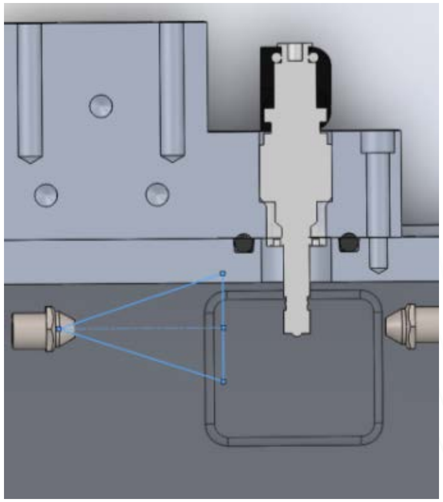


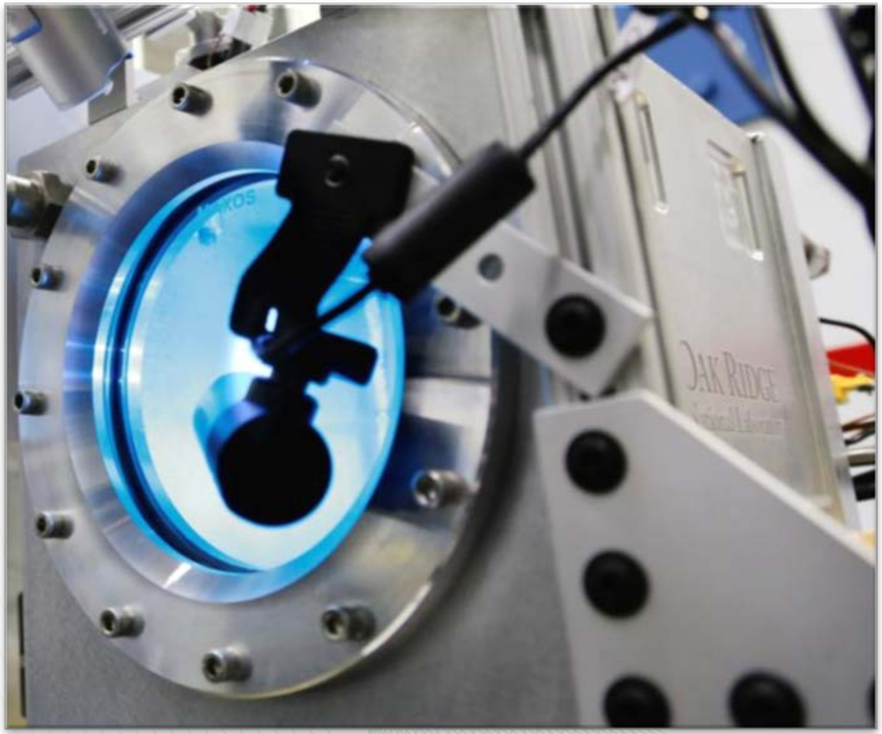
Spray chamber designed to allow for high sweep gas flow, sub-ambient P and elevated temperature

2nd generation chamber

- Multiple cartridge heaters for fuel injector and chamber temperature control (>100°C)
- Modular injector holder built to allow multiple injector designs
- Wide pressure range: 0.01 to 2 bar absolute (next generation target 6 bar)
- Direct heated sweep gas with high flowrate pumping system (>45 slpm)

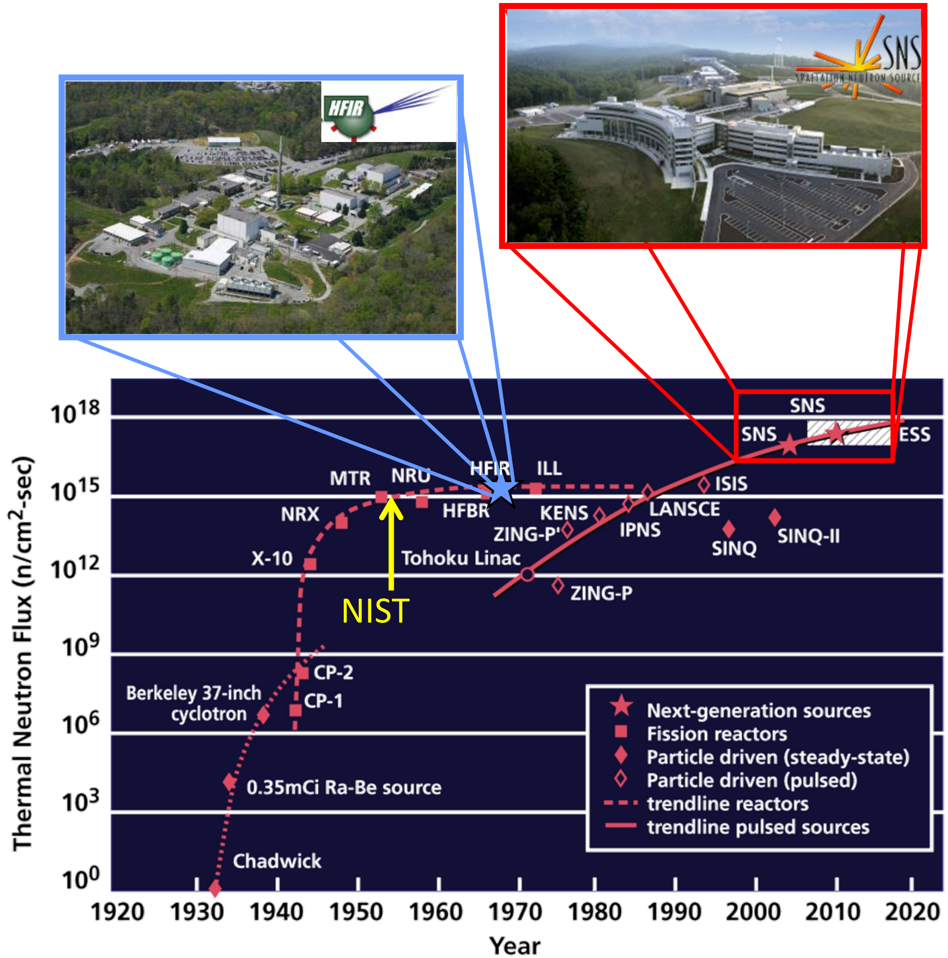




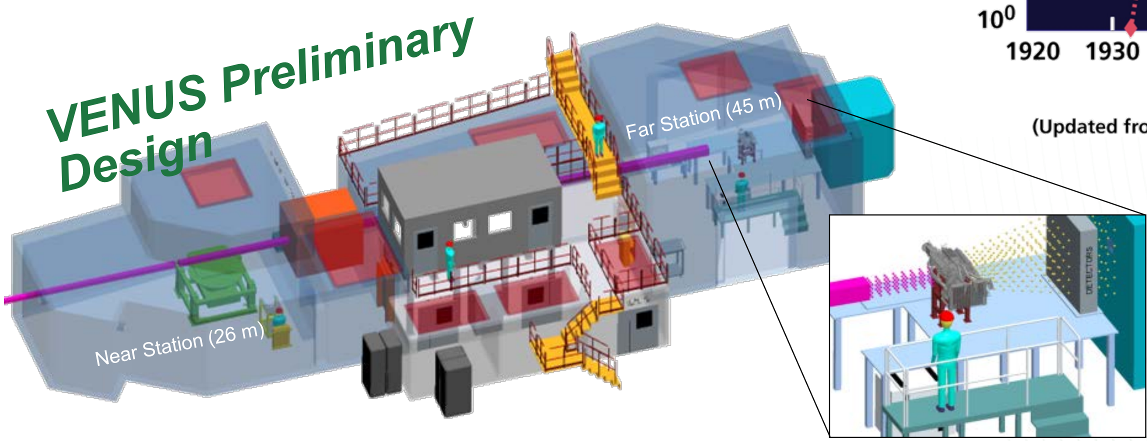


Neutrons at ORNL

- High Flux Isotope Reactor (HFIR)
  - Steady (i.e., non-pulsed) neutron source; “white” beam
  - Imaging beam line accessible through user program
- Spallation Neutron Source (SNS)
  - Most intense pulsed neutron beam in the world; energy selective
  - EERE promised $12M to VENUS imaging beamline



(Updated from *Neutron Scattering*, K. Skold and D. L. Price: eds., Academic Press, 1986)

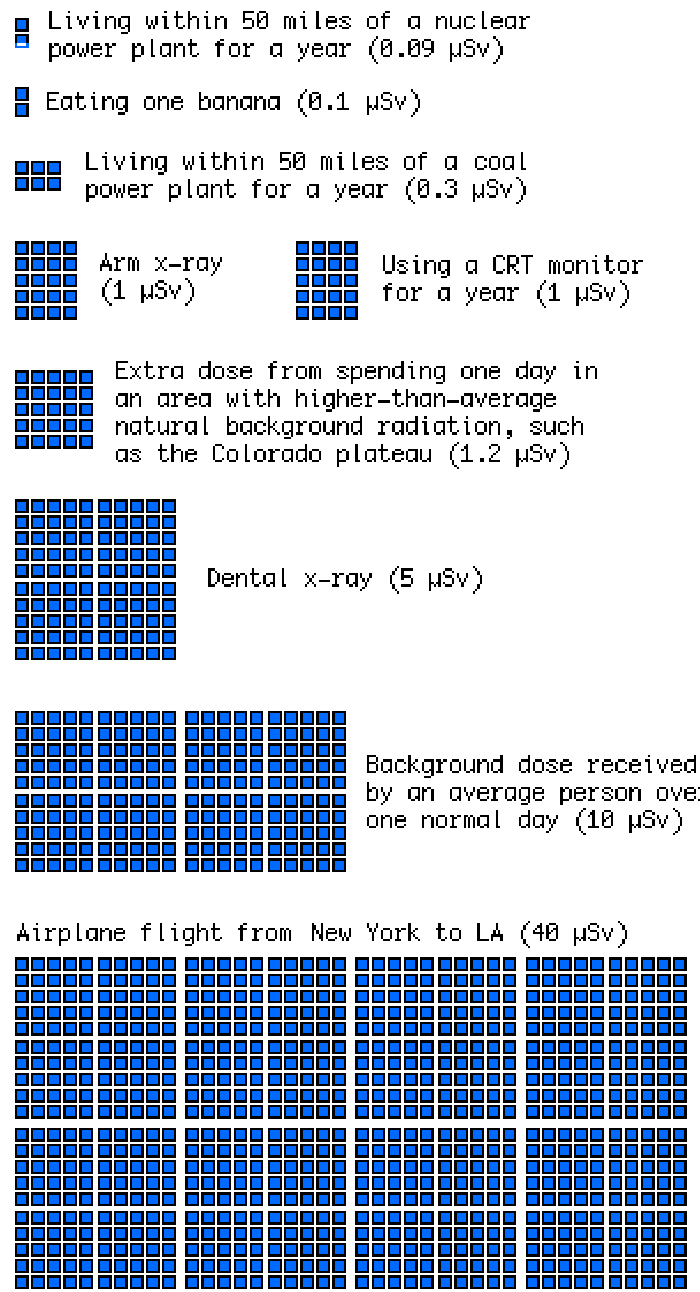


Estimated Beam Characteristics			
Resolution	20 µm	50 µm	200 µm
Max Field of View (cm x cm)	2 x 2	20 x 20	30x30

OAK RIDGE National Laboratory | NATIONAL TRANSPORTATION RESEARCH CENTER

Radiation/Activation

- Average radiation exposure
  - Working at 12 h HFIR, handling specimens: 10-20 µSv
  - Airplane trip Knoxville to DC: ~10 µSv
  - 1 day on earth: ~10 µSv
  - Chest CT-Scan: 7000 µSv
- After exposing materials to neutron beam, they can become “activated”
  - materials give off radiation as they return to their stable state
  - Time of decay varies for materials and time-in-beam
- SiC particulate filters (PFs)
  - After 20 hour CT scan
    - Can be handled within 10 minutes
    - Can be removed from facility within 1 day
- Injectors
  - After 20 hour CT scan
    - Can be handled within 30 minutes
    - Can be removed from facility after ~1 year



“source”: Randall Munroe's Radiation Dose Chart (http://xkcd.com/radiation/)